SEARCHING FOR QUARK AND LEPTON COMPOSITENESS AT THE SSC

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Summary

We examine a variety of issues connected with searching for compositeness at the SSC. These include effects of resolution, alternative methods of looking for deviations from QCD predictions, advantages of polarized beams, and effects of compositeness on photon detection. We also consider how physics may look if the compositeness scale is as low as a few TeV.

Introduction

The idea that quarks and leptons might be composite has a strong appeal. (For reviews see Peskin[1] and Bars[2]). Compositeness could provide an explanation for the repetitive structure of the generations and the origin of the fermion mass matrix, two of the outstanding puzzles of particle physics. Moreover, it is quite possible that the scale of compositeness, Λ , is within reach of the SSC. Current experiments set limits "only" of order a TeV on Λ [3,4] while many theoretical ideas suggest that Λ might be no more than a few orders of magnitude larger than the weak scale.

In theories without fundamental scalars (technicolor), in particular, quark and lepton masses must arise from physics in the TeV range, so this is a natural compositeness scale. Of course, quarks and leptons might not be composite, or the scale of their binding could be much greater than a TeV. If there are fundamental scalars, for example (as in supersymmetry), there is no reason that the quarks and leptons should not appear as fundamental down to the Planck mass. But all of us feel that compositeness just might be accessible to the SSC, and that it is something for which both theorists and experimenters must be alert.

Much work has already been done concerning searching for compositeness at the SSC, especially by Eichten, Hinchliffe, Lane, and Quigg[5] (EHLQ). In this section, we consider a number of more detailed questions.

On the theoretical side, there are a limited number of ideas and models from which we can receive some guidance. Most of us believe that any underlying preon theory will be an asymptotically free gauge theory, similar in some respects to QCD. The constituents of this theory, the preons, will be chiral fermions (and possibly fundamental scalars); this theory almost certainly will not preserve parity, to any approximation. At low energies, corresponding to wavelengths much larger than the scale of preon binding, Λ , the only modification to the standard model Lagrangian will be the appearance of non-renormalizable interactions such as four-fermi terms, form factors, and the like.[1-4] As the energy grows, quarks and leptons should reveal their true nature as strongly interacting particles--quark-quark (and lepton-lepton) scattering should resemble proton-proton scattering, with a cross section which is geometrical, and exhibits a great deal of structure. At scales much above Λ (if we may be permitted to dream, for a moment), we should resolve the fundamental preons, and physics should again scale. This QCD analogy has been pushed quite hard in past work, and we have pushed it a bit harder at this workshop.

Beyond this, we can get some guidance from experimental limits on rare processes and from existing models. In particular, Bars[6] has provided a catalog of some of the models which pass existing theoretical and experimental tests. (Unfortunately, one cannot say with certainty what the light spectrum of these theories is, nor does one have a theory for quark and lepton masses, but these models at least have the potential to be realistic). He has also listed some of the constraints which follow from limits on rare processes. In particular, some of the possible effective 4-fermi terms must have couplings smaller than $(40\ \mathrm{TeV})^{-2}$, almost certainly a difficult constraint to satisfy in model building, as experience in technicolor has shown.

Beginning with the pioneering work of Abolins et al., at the 1982 Snowmass Workshop,[3] there has been a great deal of effort to determine how one might search for compositeness at energies below Λ. In particular, Abolins et al. noted that the largest effects, in quark-quark (and lepton-lepton) scattering were likely to come from four-fermi operators, rather than from form factors, and they studied these operators in a variety of processes. Eichten, Hinchliffe, Lane and Quigg (EHLQ)[5] have extended these analyses to SSC energies. Focusing on one particular operator,

$$L_{qq} = \eta_0 \frac{g^2}{2\Lambda^2} \bar{q}_L \gamma^\mu q_L \bar{q}_L \gamma_\mu q_L \tag{1}$$

where $g^2 = 4\pi$ (by analogy to the ρ coupling), $\eta_0 = \pm 1$, they studied deviations from QCD predictions for high $p_\perp$ single jet production, for fixed beam energy. They argued that the SSC could set a limit on Λ of 20 TeV in this way (Assuming $\sqrt{s} = 40$ TeV, $L = 10^{33}$ cm^2/sec). In lepton production they showed that one could set an even stronger limit. Calling the quark-lepton coupling

$$L_{q\ell} = \eta' \frac{g^2}{\Lambda'^2} \bar{q}_L \gamma^\mu q_L \bar{L}_L \gamma_\mu L_L \tag{2}$$

they found that the SSC could set a limit $\Lambda' = 40$ TeV, by looking at deviations from QCD predictions for lepton pair production as a function of invariant mass.

At this workshop, we examined several detailed questions in this general framework. We investigated whether momentum resolution, for both leptons and jets, would significantly alter the claims of EHLQ. Following a suggestion of Pilcher,[7] we considered the advantages of varying the beam energy and studying the cross section $p_\perp^5\, d\sigma/d^3p$ at fixed $x_\perp = 2p_\perp/\sqrt{s}$. This quantity has the virtue that in the parton model it scales (it is a function of $x_\perp$ only), while in QCD it is a rather slowly varying function of $p_\perp$. If there is a hard component in quark-quark scattering, one should observe quite substantial deviations from scaling. This test should not be as sensitive as the measurement of the absolute rate to one's knowledge of structure functions and higher order corrections. We also examined the deviations in jet angular distributions which might arise from compositeness.

Our group considered two issues of some relevance to machine and detector development. We studied the possible virtues of polarizing the beams and measuring parity-violating asymmetries. This is clearly of value if deviations from QCD predictions are observed, in helping to determine the Lorentz structure of the new interactions. We found that polarization might also improve slightly the limits one could set on Λ from jet cross-sections. In addition, we studied the virtues of photon detection [see also Owens et al., these Proceedings[8]]. We found that, even though the rate is low, since photons represent a relatively clean signal, one should be sensitive to compositeness scales as high as 10 TeV.

Our group examined two issues beyond the framework of flavor-independent contact interactions employed in EHLQ. First we asked: suppose the scale of compositeness is relatively low, say a few TeV. Then one might hope to see some spectacular signatures: structure in cross-sections and multiquark and lepton production. Reasoning by analogy with QCD, a quite detailed model for these cross-sections was developed (see also Bars[9] and Bars and Albright,[10] these Proceedings). The principle observation is that, since one expects confinement and formation of flux tubes, a string-like picture with amplitudes similar to those of the Veneziano model should emerge. The resulting model exhibits a great deal of structure, and total cross-sections which grow logarithmically at high energies. It should be useful as an indicator of how finely one can resolve structure at the SSC.

Usually one assumes that the contact interactions are approximately flavor-independent, since this is the simplest way to avoid flavor-changing neutral currents and rare decays. However, it is possible that such processes are avoided by more intricate means, and that the four-fermi interactions exhibit some flavor dependence. This possibility is, in fact, suggested by some models, and should be kept in mind. Members of our group considered possible violations of universality in lepton production, especially in τ production (see also G. Snow, these Proceedings[11]).

Abolins et al. considered at some length the properties of possible new particles (exotic quarks and leptons) which might appear in composite models. While we left this subject largely to the Exotics group, we comment here that 3-body decay modes ignored by Abolins et al. are likely to be as important as the 2-body modes they considered.

This contribution is organized into sections, one for each of the topics listed above.

Effects of Detector Resolution

While discussing the possible contributions of composite models to processes such as $pp \to \ell^+\ell^- x$, a question arose concerning the experimental requirements on mass resolution. The worry was that a large error on the mass, when convoluted with the steeply falling Drell-Yan cros section, might mimic and therefore mask additional contributions.

Two comments are immediately in order. First, if the detector resolution is known as a function of mass, then there is no effect, as the resolution can be unfolded from the measured cross-section. Second, in the region of interest, that is high di-lepton masses, the standard cross-section has flattened out slightly.

To see the expected size of possible effects due to detector resolution, we have convoluted the advertised momentum resolution for muons at the SSC (~15% at 500 GeV/c, rising linearly to ~30% at 2000 GeV/c), with the Drell-Yan cross-section $d\sigma/dM\,dy|_{y=0}$ given in EHLQ, Figures 8-16. Without correcting for the mass resolution, the contribution of low masses spilling into the high mass region is such that the integrated cross-section increases by 3% above 1 TeV/c^2 and by 12% above 1.4 TeV/c^2. Note that even if the mass resolution were a constant 30%, the uncorrected effect in the integrated cross-section would be 22% above 1 TeV/c^2.

The case of $pp \to 2$ jets $+ x$ may be more interesting in that the total cross-section is larger and it may be more difficult to unfold the detector resolution. Using the cross-section given in EHLQ, Figures 3-22, for jet-pair masses and an energy resolution for jets of 10%, one finds an increase in the uncorrected integrated cross-section of 17% above 5 TeV/c^2. If the jet-pair mass resolution is as bad as 20%, then the uncorrected integrated cross-section is increased by 54%.

EHLQ suggested that one search for compositeness by looking for a factor of two deviation from QCD predictions. If one imposes such a criterion in practice, it appears that detector resolution is not likely to be a serious limitation in searching for compositeness.

Scaling Violations in $x_\perp$

The methods which have been discussed for looking for contact interactions all involve looking for deviations from QCD predictions. For example, EHLQ suggest looking for increases of a factor of two in single jet and lepton pair production. One might worry that there are uncertainties in the QCD predictions of this order, coming from higher order terms in the perturbation expansion and from uncertainties in the structure functions. It is widely believed that, by the time the SSC turns on, the structure functions will be known over the required x and Q^2 range to better than 20%.

To get some notion of the size of higher order QCD effects, we performed a simple exercise. We computed the single jet cross-sections, as in EHLQ, as a function of $p_\perp$ at $y=0$. But, instead of taking $Q^2 = p_\perp^2$, for the argument of the structure functions and the couplings, as in EHLQ, we took $Q^2 = p_\perp^2/4$. This led to changes in the cross-section of no more than 25% over the $p_\perp$ range of interest. Thus, the criteria employed by EHLQ for establishing the existence of contact terms are probably reasonable.

An alternative approach for searching for contact terms has been suggested by Pilcher.[7] In the naive parton model, the quantity $p_\perp^3 \frac{d\sigma}{dp_\perp dy}$ is a function only of $x_\perp = 2p_\perp/\sqrt{s}$. In QCD, this scaling behavior is slightly modified due to the Q^2-dependence of the coupling constant and structure functions. In the multi-TeV range relevant to the SSC, roughly

$$p_\perp^3 \frac{d\sigma}{dp_\perp dy} \sim p^{-.4} f(x) \qquad (3)$$

(See Figure 1, below)

Of course, if contact terms are present, there should be dramatic deviations from scaling as we approach the scale Λ. Observations of such scaling violation might be more convincing than simple deviations in the raw rate. With this in mind, we have plotted $p_\perp^{3.4}\, d^2\sigma/dp_\perp dy$ vs. $x_\perp$ in Fig. 1, using the contact term in EHLQ (Eq. 1) with $\eta = -1$, and $\Lambda = 25$ TeV, as well as the pure QCD prediction, for several values of the beam energy.

The data points represent $x_\perp$ bins of 0.04 per unit of rapidity. At $x_\perp = 0.28$, there are approximately 200 events per bin for an integrated luminosity of 10^{40}. The scaling violations are quite dramatic, so this technique could provide convincing evidence of contact interactions, to rather large values of Λ.

Clearly one concern will be the linearity of the detectors over the wide range in $p_\perp$ required (0.5-6 TeV). It would obviously be desirable to run at several energies so as to minimize such systematic uncertainties.

Angular Distributions

If deviations from QCD predictions for jet cross-sections are observed, one will want to obtain as much information as possible about their underlying cause. One might hope, from jet angular distributions, to provide further evidence for contact interactions, and to learn about the form of these interactions. In Fig. 2, we have plotted the jet cross-section for pure QCD, at $y_{boost} = 1/2(y_1 + y_2) = 0$, as a function of $y^* = 1/2(y_1 - y_2)$. In Fig. 3, we have plotted the same quantity with two forms for the contact interaction. One is the pure left interaction of Eq. (1); the second is a pure vector interaction, (Please see next page)

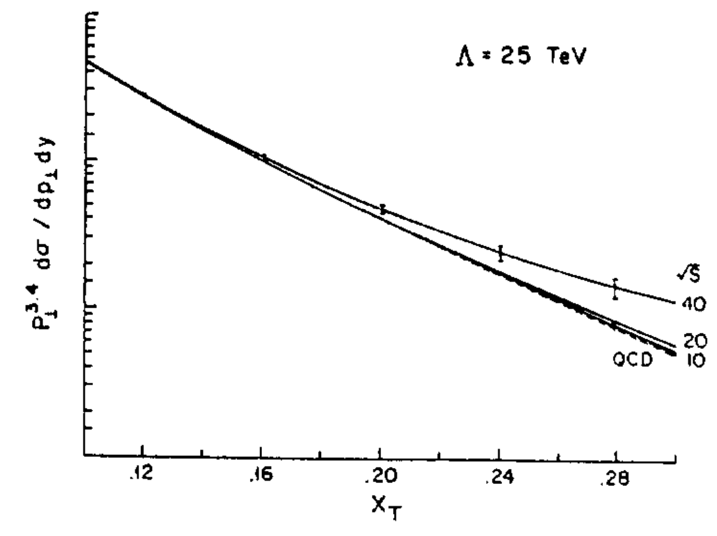

Figure 1. Predictions for $p_\perp^{3.4}\, d\sigma/dy\, dp_\perp$ vs. $x_\perp$ for different values of s .

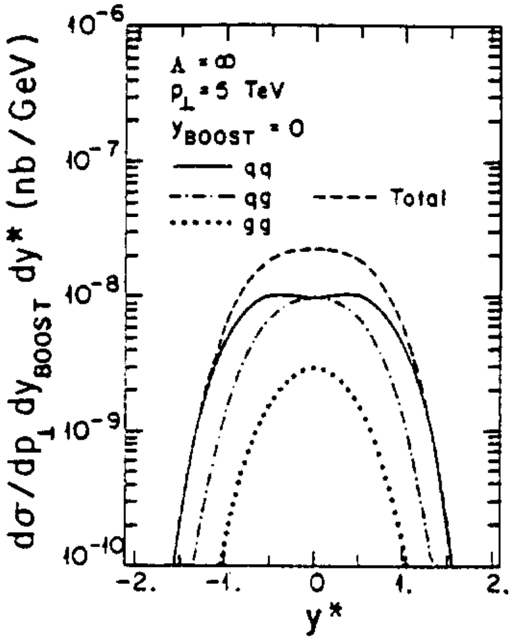

Figure 2. Prediction for $d\sigma/dy^*dp_\perp$ for $y_{boost} = 0$, $\Lambda = \infty$.

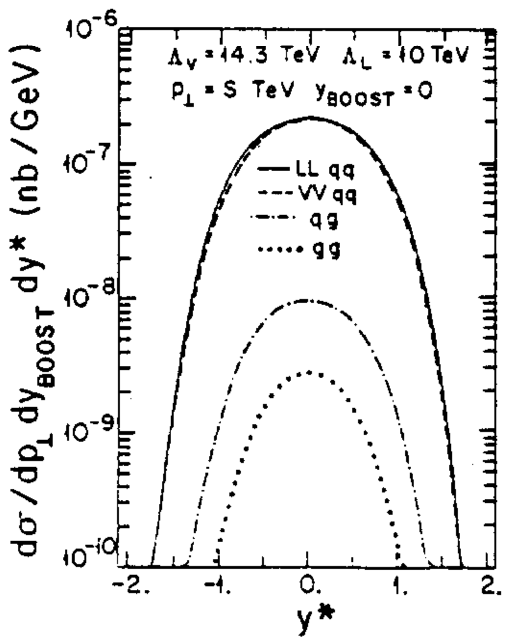

Figure 3. Same as Figure 2, with two types of contact interaction.

$$L_{VV} = \frac{1}{2}\frac{g^2}{\Lambda^2}\,\eta\,\bar{q}\,\gamma^\mu\,q\,\bar{q}\,\gamma_\mu\,q \tag{4}$$

so that the curves will coincide, we have taken $\Lambda = 10$ TeV for the first case; $\Lambda = 14.3$ TeV for the second. In both cases, $p_\perp = 5$ TeV/c, and $\eta = -1$.

As one may see from the figures, the QCD distribution is distinctly flatter than the distribution in the presence of contact interactions. Unfortunately, the angular distributions for the LL and VV cases are virtually identical. This is also true for $\eta = +1$ (not shown). Thus, angular distributions are likely to provide further evidence of compositeness, but probably won't be too helpful in determining the form of the underlying contact interactions.

Polarization

Any new interactions binding preons into quarks are almost certainly parity violating. Thus, one might hope to get a handle on composite structure by searching for parity violation beyond that expected from electroweak interactions. In particular, parity violating asymmetries in polarized pp scattering would be a useful tool in searching for and disentangling any composite structure.

There are two ways in whicn polarized beams could play a role in exploring compositeness. First, if significant deviations from QCD predictions for, e.g., jet cross-sections are observed, polarization could help determine the structure of the corresponding contact interactions. Obviously, if we had polarized quark beams, this would be rather easy. However, even in the real world of polarized protons, a good deal is known about the parton structure functions for different helicities, so it should be possible to determine a good deal about the helicity structure of the underlying interactions.

One might also hope that polarized beams would increase one's sensitivity to composite structure altogether. In particular, one might hope to set larger limits on Λ than one can set by looking at, say, the inclusive single jet rate. Such a study, for CBA energies, has been performed by Paige and Tannenbaum.[12] We have scaled this computation up to SSC energies.

The key to our analysis is a result due to D. Hochberg,[13] who has studied extensively the spin-dependent Altarelli-Parisi equations. He has found that, to a good approximation, a prescription due to Carlitz and Kaur[14] for obtaining polarized structure functions from unpolarized ones commutes with QCD evolution. In other words, we may take the distribution functions given by EHLQ at a given Q^2, and operate on them with the Karlitz-Kaur prescription to find the polarized structure functions at that Q^2. In fact, following Paige and Tannenbaum,[12] we used an even simpler prescription, obtaining the structure functions from SU(6) relations. Thus,

$$u_{++} = 5/6\,u \qquad u_{-+} = 1/6\,u$$
$$d_{++} = 1/3\,d \qquad d_{-+} = 2/3\,d \tag{5}$$

Here the first subscript denotes the quark helicity, while the second denotes the proton helicity.

In order to compute the electroweak contribution to the asymmetry, we used the results of Ranft and Ranft,[15] who have computed the relevant QCD-electroweak interference terms. For the compositeness contribution, we take the same interaction as in EHLQ, Eq. (1). This interaction is pure LL; thus it vanishes for all incoming quark polarizations except left-handed quarks on left-handed quarks. We have computed the quantity

$$\Delta = \frac{\frac{d\sigma^{++}}{dp_\perp dy} - \frac{d\sigma^{--}}{dp_\perp dy}}{\frac{d\sigma}{dp_\perp dy}} \qquad (6)$$

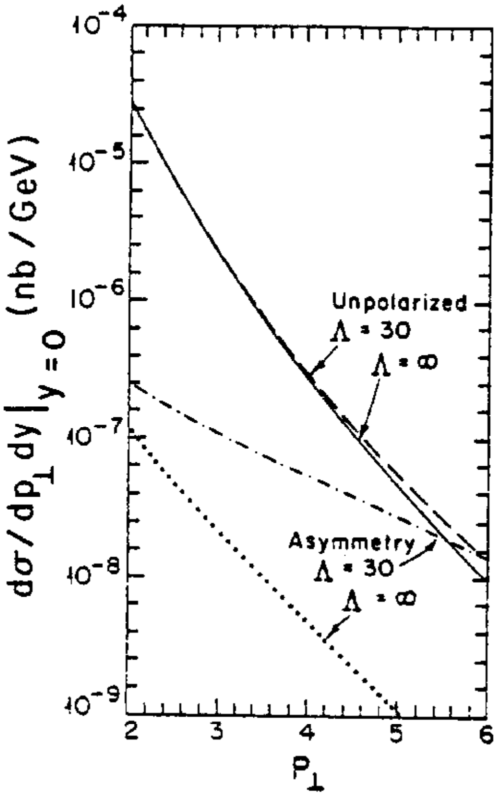

Figure 4. Parity violating asymmetries for the standard model and the contact term with $\Lambda = 30$ TeV.

The results are shown in Fig. 4, above, for $\Lambda = 30$ TeV. In order to determine what limits one might set on Λ, we have tried to develop a criterion similar to that of EHLQ. First, we note that, in the absence of compositeness, Δ turns out to be less than 10% over the entire range of $p_\perp$. To be conservative, we require that Δ be larger than 20%. Following EHLQ, we also require that there be at least an excess of 50 events in a 100 GeV bin in $p_\perp$, for an integrated luminosity of 10^{40} cm^2. Then we find that one can set a limit of 30 GeV on Λ. This is compared with the 20 GeV limit from jets (and the 40 GeV limit from lepton pairs) suggested by EHLQ. If one requires that there be an excess of 50 events in all momentum bins above a certain value, one does not improve the limit significantly.

Thus, polarization slightly improves the limits one can set on Λ over those from jets, but one can still obtain a better limit from lepton pairs. Further detailed study of how well one can do in disentangling the various types of contact interactions would certainly be desirable. As a simple, but interesting, example, note that the asymmetry (6) is equal in magnitude and opposite in sign for pure left-left and pure right-right interactions.

Direct Photons

Direct photons at high $p_\perp$ are clearly interesting probes of quark-quark interactions, and they have been the subject of some interest at this conference (see, e.g., G. Feldman, these Proceedings[16]). Clearly, if quarks show structure on SSC energy scales, the single γ production cross-section will be harder than expected from QCD. This issue was considered by members of our group and a detailed discussion appears in these Proceedings. Here we will just summarize the major findings.[8] In QCD, the principal source of direct photons is a Compton-like process, in which a gluon scatters from a quark, which emits a photon. Bremstrahlung processes also make a sizable contribution, though this falls rapidly at large $p_\perp$. If quarks are composite, there will be additional contributions. These can be described, for $p_\perp \ll \Lambda$, by contact interactions. The lowest dimension operators which can contribute have the form

$$\epsilon^{\mu\nu\rho\sigma} \frac{e F^{\gamma}_{\mu\nu}}{\Lambda^2} \bar{q} D_\rho \gamma_\sigma q \qquad (7)$$

where D_μ is the covariant derivative (and thus includes a gluon coupling). Such an interaction would arise, for example, from production of an off-shell, excited fermion. This gives a contribution to the amplitude for $qq \to \gamma q$ of size $\hat{s}/\Lambda^2$ relative to the QCD contribution, and thus dominates once the subprocess energies are of order Λ. For $\hat{s} > \Lambda^2$, we would expect the cross-section to become roughly constant, of order α times the total cross-section. Of course, it might exhibit interesting structures, such as resonances, on scales of order Λ.

Because photons are comparatively clean, one can tolerate relatively low rates. From QCD alone, Owens et al. find that with $p_\perp = 3$ TeV there are about 54 events in a 1/2 TeV bin per year. If $\Lambda = 10$, using the contact interaction above, this number is about doubled. So, direct photons can provide access to scales of about 10 TeV.

Crossing the Compositeness Scale

It is possible that the scale of compositeness is only a few TeV. In that case, at high transverse momenta the quarks and leptons should appear as strongly interacting particles. Their cross-section should exhibit structure, such as resonances, and presumably will tend to a constant, geometrical value, of order $10\pi/\Lambda^2$ for quark-quark scattering, and of order α_s times smaller for gluon-quark scattering. Multiple quark and lepton production should be common, with multiplicity distributions similar to those of conventional hadron physics.

Such a situation, at the SSC, should be quite striking. Of course, since we don't have monochromatic quark beams, it is natural to ask how much of this structure we will be able to resolve. Towards this end, a quite detailed model for quark-quark and quark-gluon scattering was developed. We refer the interested reader to the work of Bars[9] and Albright and Bars[10] for the details, and summarize the principle results here.

As discussed in the Introduction, we expect the dynamics of the underlying preon theory to be similar, in many respects, to that of QCD. In particular, we expect confinement, described by pre-color flux tubes. Thus, composite fermions and bosons might well lie on linear Regge trajectories, reflecting approximate string dynamics. The major difference from QCD is that the preon theory necessarily has (almost) massless fermions (the quarks and leptons), rather than massless pions. Also, to explain the lightness of the quarks and leptons, the preon theory must have a high degree of unbroken symmetry, so the spectrum should show large, approximate degeneracies. Using Regge Pole and duality arguments, and making some simplifying assumptions about the spectrum, a detailed model with a great deal of structure was constructed in this way, for both quark-quark and gluon-quark scattering. Note that gluon-quark and gluon-gluon scattering may be quite important if the scale of compositeness is small, since the gluon distributions are so large at low x.

For reasons of time, we have not been able to produce results for these detailed models. Of course, it is not clear how much detailed structure will be visible once the cross-sections are folded with the parton distributions. One case where a similar type of structure has been considered for the SSC is technicolor. There, EHLQ[5] have included techni-vector mesons in certain production cross-sections. Not much structure survives; these resonances appear as broad enhancements, if at all (see, e.g., EHLQ, Figs. 6.10 - 6.13).

In our case, some care will have to be taken in how data is plotted. For example, jet cross-sections at fixed m^2 integrated over $p_\perp$ and y^* blow up, due to the QCD contribution which blows up at $t=0$. So, one may wish to plot cross-sections as a function of m^2 with a lower cutoff on $p_\perp$, or as functions of $p_\perp$, or in some other way. As a simple first exercise, we did the following:

We assumed a neutral resonance in the s-channel, of mass Λ, width Λ/s, and coupling g. We plotted $d\sigma/dM\,dy$, with a cutoff on $p_\perp$, for various values of Λ. Also, to avoid being swamped by gluons, we included only the quark-antiquark component of the cross-section. For $\Lambda = 3-6$ TeV, and $p_{\perp min} = 0.5-2$ TeV, no structure was visible in the cross-section. This is clearly an area for further work, however. Perhaps more ingenious cuts, or focusing on leptons, can enhance structure.

Compositeness in the $\tau\bar{\tau}$ Channel

Among the prinicple attractions of compositeness are that it might explain the generation puzzle and the origin of quark and lepton masses. If compositeness is somehow tied to the breaking of $SU(2) \times U(1)$ (as in extended technicolor), then scales of order a few TeV may be contemplated. The major constraint on such ideas comes from rare processes. Large suppressions of strangeness changing and lepton number violating processes must somehow be arranged. This can occur if the theory has, in some approximation, a very high degree of symmetry among the generations. For example, in EHLQ, it was assumed that the four-fermi interactions are flavor blind; this automatically conserves all quark and lepton flavors. However, it is not easy to construct models with so much symmetry.[6]

Thus, if compositeness occurs at scales less than 40 TeV, rare processes might be avoided by some more intricate means.

With this in mind, George Snow considered the possibility that compositeness leads to a significant enhancement of τ pair production, but not much additional e or μ production. This idea was motivated by two classes of models. One, due to Pati,[17] in which there is a lower compositeness scale for heavy quarks and leptons than light ones; one, due to Bars,[9] in which the τ's are in the same family as the u and d quarks. In the first case, the principle four-fermi terms couple b and t quarks to τ leptons; in the second they couple u and d quarks to τ leptons, with e and μ couplings suppressed by mixing angles. No matter how seriously one entertains either class of models, it is clearly quite important to keep in mind the possibility of some non-trivial flavor dependence and violations of universality, and τ identification is thus desirable.

Most of Snow's calculations (performed in collaboration with K. Lane) are for the Pati-type model. For the Bars-type model, one can determine the rates as a function of mixing angles simply by examining Fig. 8-16 in EHLQ, and multiplying by any assumed mixing angle. With interaction

$$L = \frac{4\pi}{\Lambda^2}\, n \left[\bar{b}_L \gamma_\mu b_L \bar{\tau}_L \gamma^\mu \tau_L + \bar{t}_L \gamma_\mu t_L \bar{\tau}_L \gamma^\mu \tau_L \right] \quad (8)$$

Snow finds that, for $\Lambda = 4.5$ TeV, the cross-section is $\left.\frac{d\sigma}{dy}\right|_{y=0} = 1.11 \times 10^{-5}$ nb, a factor of ten larger than the pure QCD rate. τ's may not be too hard to detect, because of the low multiplicities of their decay products. After considering various backgrounds, Snow concludes that a factor of ten enhancement in the τ-signal is detectable, so that in models of this type, Λ's up to about 5 are detectable.

Determining, more generally, the sensitivity of the SSC to violations of universality will depend clearly on how well one understands the detection efficiency for e's, μ's, and τ's.

New Particles Predicted by Composite Models

While no truly complete or compelling model of composite quarks and leptons currently exists, many of the toy models which have been studied,[1] as well as the classification of models by Bars,[6] suggest that such a theory might contain relatively light exotic states: colored particles with lepton number, color sextets, and so on. (Of course, among the highly excited states, there will certainly be excitations with such quantum numbers. Here we are interested in states with masses below Λ). The production and decays of such particles can be analyzed in the same fashion as hard quark scattering. One writes down operators of the lowest dimension which can produce the desired decay and which obey the conjectured symmetries. This topic was the subject of extensive discussion in the 1982 Snowmass Proceedings, and also in the Exotics group at this conference. We wish to add only one point to those discussions:

It is usually assumed that the decays of such exotics occur through magnetic moment-type couplings. However, the four-fermi operators whose role was so heavily stressed by Abolins et al.[3] for scattering seem likely to be equally important here. First, there is not likely to be any particular suppression due to quantum numbers. For almost any conceivable exotic, there is some conventional three-body final state with correct helicity, color, and lepton number. Second, just as the coupling $g^2 \sim 4\pi$ enhances the four-fermi operators over the form factors in hard quark scattering, so this factor, in decays, compensates for the extra suppression due to three-body phase space. In general, then, we would advise those considering exotic decays to be mindful that three-body final states are likely to be as important as two-body states.

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